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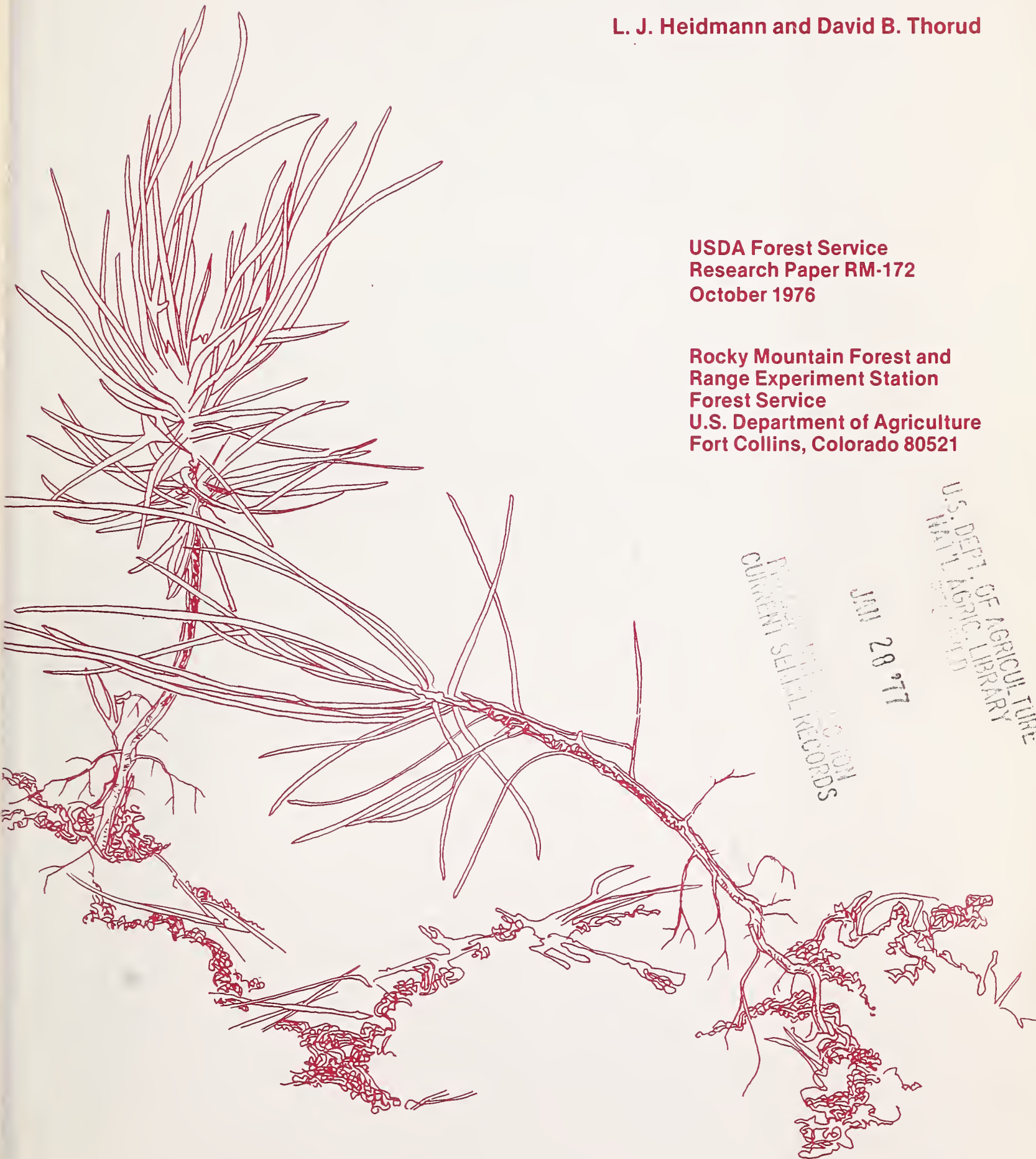
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Controlling Frost Heaving of Ponderosa Pine Seedlings in Arizona

L. J. Heidmann and David B. Thorud

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Rocky Mountain Forest and
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Frost heaving is a three-step process: (1) The surface layer of soil freezes and grips the seedling stem tightly. (2) Ice lenses form below the surface, lifting the seedling and frozen soil. (3) When the soil thaws, it settles back loosely to its original position, leaving the seedling on the surface. Plowing to reduce soil bulk density and adding gypsum to lower the freezing point of soil water will reduce frost heaving.

Keywords: Frost heaving, regeneration methods, *Pinus ponderosa*.

**Controlling Frost Heaving of
Ponderosa Pine Seedlings in Arizona¹**

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HIGHLIGHTS AND RECOMMENDATIONS

Frost heaving is the result of the formation of ice lenses in the soil caused by a segregation of the soil water. Segregation occurs because of supercooling of adsorbed water and water in small soil pores. The difference in freezing points between free water and supercooled water provides the energy to draw water to the freezing zone and lift the soil.

Tree seedlings heave when the surface layer of soil freezes solid and grips the stem tightly. The formation of ice lenses below the surface lifts the tree and the frozen soil. When the soil thaws, it settles back into approximately its original position, while the tree remains extruded on the surface. Time-lapse photography confirms that heaving is usually the result of several freeze-thaw cycles.

Frost heaving of six Arizona soils studied was closely related to bulk density. Heaving increased with compaction, most likely as the result of improved capillary flow. Studies in the laboratory and the field revealed that several chemicals, at rates not toxic to ponderosa pine, reduced heaving. In the laboratory tests, calcium chloride and ferric chloride significantly reduced total heaving, and lengthened the time required to initiate freezing more than other chemicals tested. In the field, survival was highest for tubelings planted in plots treated with gypsum, and for plug seedlings planted on plots treated with calcium chloride. Heaving of tubelings and plugs

was least on plots treated with sodium tetraphosphate and gypsum. Tests of coarse sand and various methods of planting gave mixed results. Observations in the field indicated that heaving does not occur until the soils are very wet—at least 50 percent moisture content on an oven-dry weight basis.

Current knowledge indicates several steps that can be taken to reduce frost heaving damage when regenerating ponderosa pine from seed.

- Frost heaving of Arizona soils is closely related to bulk density, therefore measures to lower the bulk density are advised. These include plowing and disking the areas to be regenerated. This treatment will not only lower the bulk density but will also eliminate competing vegetation. Gypsum may be added to the soil when it is plowed. The calcium ion in the gypsum will lower the freezing point of the soil water, while the sulfur has a fertilizing effect.

- Freshly burned areas should be seeded as soon after the burn as possible. If dead trees are left standing to provide shade, a more continuous snow cover will be retained throughout the winter. The insulating effect from the snow should reduce frost heaving damage considerably. If possible, burned areas should be plowed to reduce the bulk density, and also to break up the heat-caused hydrophobic soil layer near the surface.

- In all cases, compacting the soil in regeneration areas should be avoided.

INTRODUCTION

Frost heaving is a serious problem in the regeneration of many tree species. In northern Arizona it is a major cause of first-year mortality of ponderosa pine (*Pinus ponderosa* Laws.) seedlings. Frost heaving destroyed 52% of the seedlings in a seedling study during 1 night in October (Larson 1961).

Despite the fact that it is a serious problem, frost heaving has not been studied intensively by foresters or workers in other allied agricultural fields. For these reasons, an intensive study of the frost heaving phenomenon was started in northern Arizona in 1972.

The study consisted of several parts. First was an examination of the literature pertaining to frost heaving. Second was an attempt to predict frost heaving susceptibility of different Arizona soils by measuring various soil parameters

in the field and the laboratory. Next, experiments were conducted in the laboratory and the field to determine if methods of controlling frost heaving could be found. Finally, the frost-heaving phenomenon was observed in the field with a time-lapse camera.

SUMMARY OF LITERATURE REVIEW

The literature review (Heidmann 1976) revealed that frost heaving is primarily a soil surface phenomenon resulting from a segregation of soil water that freezes into layers of ice variously referred to as lenses, needle ice, stalactite ice, or comb ice (kammeis) (Schramm 1958). Tree seedlings heave because the surface soil layer freezes solid first, and grips the stem tightly. According to Schramm (1958), this occurs because the soil particles near the surface are coarser than particles

lower in the soil, and are surrounded by larger pores. Water in the larger pores freezes at close to 0°C. Below the solidly frozen soil surface layer, the soil water segregates, and subsequently freezes into lenses which lift the surface with the tightly held seedling. Upon thawing, the tree remains in an extruded position on the soil surface, while the soil recedes to approximately its original position. Frost heaving of seedlings is usually the result of several freeze-thaw cycles, although in theory only one is needed.

The soil water segregates within the total matrix because of supercooling (referred to as undercooling in much of the literature) of water in the smaller pores and water adsorbed on soil particles. The difference in freezing points between free water and water in the smaller pores provides the free energy needed to draw water to the freezing front and to lift the soil surface.

To maintain the growth of clear ice needles at a point, the vertical flow of water to the freezing front must match the fusion rate: 1 g of soil water must be supplied for each 80 cal of heat (1 g of water releases 80 cal of heat upon freezing) flowing through the ice lens to the soil surface. If either the heat flow to the surface becomes too large or the supply of water becomes limiting, segregation of the water will stop and water will freeze in place in the soil pores (Outcalt 1969). This type of freezing is sometimes referred to as concrete frost.

Water segregates in soils that are permeable to water flow, and in which a negative pressure or tension can be developed. Both permeability and negative pressure are related to soil pore size, which is a function of soil particle size or texture. A silty soil is ideally suited to frost heaving because the pores are large enough for good permeability, but small enough for a negative pressure to develop (Penner 1958). Clay soils may heave but not because of good permeability. Heaving of clay soils is determined to a large extent by the type of clay minerals, and the nature of the ions adsorbed on the clay particles.

Frost heaving of seedlings under 1 yr of age is more common than heaving of transplants (Schramm 1958).

SUMMARY OF FROST HEAVING SUSCEPTIBILITY INFORMATION

The first experiments in the study were aimed at developing a regression equation for predicting frost heaving susceptibility of Arizona soils (Heidmann 1975). Fourteen soil parameters (table 1) were measured for six soils collected within a 40-mi radius of Flagstaff. At each of the six locations, soil was collected from three depths: 0 to 2.5,

Table 1.--Location and description of soils used and parameters studied in frost heaving experiments

Location	Elevation	Textural classification ¹	Variables studied (All soils)
	<i>feet</i>		
Tie Park (TP)	7,400	Silty clay loam	Bulk density Sand content Silt content Clay content Montmorillonite content Kaolinite content Vermiculite content Mica content Total calcium Total magnesium Exchangeable calcium Exchangeable sodium Exchangeable magnesium Cation exchange capacity
Beaverhead Flat (BF)	3,800	Sandy loam	
S-3 West, Ft. Valley (S-3,W)	7,300	Silt loam	
S-3 East, Ft. Valley (S-3,E)	7,300	Silt loam	
Watershed 14 (W14)	7,400	Silty clay loam	
Kelly Tank (Kelly)	7,200	Sandy loam	

¹As determined by hydrometer method, USDA system.

2.5 to 7.6, and 7.6 to 15.2 cm. The heaving characteristics of soil from each depth were studied in a specially constructed freezing chest, which was placed in a chest-type freezer (Heidmann 1974).

All of the 14 variables were used in a stepwise regression analysis to develop an equation for predicting heaving susceptibility. An equation was found, however, which accounted for 71% of the variation in heaving (r^2) using only two variables, bulk density and percent sand. The equation is:

$$Y = 2.52 + 3.67X_{BD} - 0.026X_{SAND}$$

where Y is heaving in millimeters per day. When the bulk density variable is used alone, the r^2 is only 0.37. Bulk density and sand have a correlation with each other of 0.60.

The prediction equation shows that frost heaving is positively correlated with bulk density. This fact became apparent with the first preliminary attempts to study frost heaving in the laboratory. Heaving was studied in polyvinylchloride (PVC) cylinders, 3.3 by 7.6 cm, filled with soil and placed in the freezing chest (Heidmann 1974). It was noted that, for a particular soil, frost heaving varied considerably with the degree of soil compaction. As a result of this finding, an experiment was conducted to study the heaving characteristics of the six soils and depths at minimum, mean, and maximum bulk densities (Heidmann and Thorud 1975). The results indicated that compacting the soil increased the rate of frost heaving for all soils and depths, but particularly at the highest bulk density.

The equilibrium moisture content of all of the samples was determined at the beginning of the freezing period. It was noted that, for each soil depth, the total weight of water was essentially the same for all three densities. This would seem to indicate that, at the lowest bulk density level, a large percentage of the pores were filled with air. As the bulk density level was increased (by adding more soil to the cylinders) the weight of water stayed the same, which indicates that the percentage of air-filled pores decreased. The most logical explanation for increased heaving with increasing bulk density is that capillary flow of water is increased by compaction.

If the soils in the study had contained a high proportion of clay, compacting would most likely have reduced heaving because of reduced permeability. All of the soils in the study, however, had moderate amounts of clay but had high silt contents. With a high silt content it is probably not possible to compact soils enough to reduce permeability.

CONTROLLING FROST ACTION: OUR EXPERIMENTAL APPROACH

There are several ways in which a soil can be made less susceptible to frost action. The first is to prevent freezing of water in the soil pores. Another is to reduce the permeability of the soil so that water cannot migrate to the freezing zone at a fast enough rate to produce ice lenses. A third method, suggested by Lambe (1956), is to cement the soil particles together with a bond strong enough to resist the expansive forces of frost action. It is also possible to prevent frost heaving by preventing supercooling of soil water.

The following experiments and observations were made in an effort to find methods for controlling the heaving of ponderosa pine seedlings.

The first experiments were conducted with various chemicals reported in the engineering literature to be successful in reducing frost heaving of highways and other structures (Heidmann 1976). The chemicals were studied in three steps. The first step was to determine if the chemicals were toxic to ponderosa pine seedlings or inhibited germination. Next, chemicals at rates not harmful to ponderosa pine were tested for their effectiveness in preventing frost heaving of two susceptible soils in laboratory experiments. The third step was to field test the most promising chemicals. The field experiments also included control methods suggested by previous observation.

Laboratory Experiments

Effect of Chemicals of Germination of Ponderosa Pine Seed (Experiment A)

The first chemical experiment was conducted to determine the effect of five compounds on the germination of ponderosa pine seeds and subsequent growth of seedlings. Number 60 (fine) sand was placed in styrofoam cups, and chemicals were mixed into the sand. Each cup was randomly assigned to receive one of the following chemical additives:

Additive	Mode of Action
Sodium tripolyphosphate (Tripoly) ⁴	Dispersing agent
Sodium hexametaphosphate (Calgon)	Dispersing agent
Ferric chloride (FeCl ₃)	Cementing agent
Calcium chloride (CaCl ₂)	Lowers freezing point of water
Calcium sulfate (Gypsum) (CaSO ₄)	Lowers freezing point of water

The levels of the additive were calculated as 0.0, 0.1, 0.5, and 1.0% of the mass of the 0- to 2.5-cm depth of the soil from Unit S-3 of the Fort Valley Experimental Forest. Larson (1961) found that frost heaving at S-3 was a major cause of mortality of ponderosa pine seedlings less than 1 yr old. The bulk density was 1.00, based on preliminary laboratory observations.

Each chemical was added dry to the cups and mixed into the top 2.5 cm of sand. Ten pine seeds were covered with 50 g of dry sand, and distilled water was added to each pot. The amount of water added was slightly less than the amount needed to saturate the sand. The cups were then placed in a growth chamber on April 14, 1972. A day length of 16 h was used. The temperature was set at a constant 24°C, and the relative humidity was about 50%. The pots were watered at least every other day with distilled water. Starting April 20, the pots were checked daily for germination of seeds until May 19, when the experiment was terminated. At the conclusion of the experiment, the total number and height of live seedlings per pot was determined.

⁴Several companies supplied materials used in the study. Sodium tripolyphosphate was donated by the FMC Corporation, New York City; sodium hexametaphosphate was donated by the Calgon Corporation, Pittsburgh, Pa.; and the Ontario tubes were provided by the Micro Plastics Company Limited, Ontario, Canada.

Effect of Chemicals on Young Ponderosa Pine Seedlings (Experiment B)

In an experiment similar to the preceding one, the same chemical treatments and rates were tested against young ponderosa pine seedlings. In this test, the chemicals were added to pots containing at least five healthy seedlings that were 4 weeks old. The mean height of the seedlings in each pot was determined to the nearest millimeter. Each chemical was dissolved in 40 ml of distilled water before being added to the pots. The trees were then allowed to grow for 1 mo during which time the pots were watered periodically with nutrient solution. At the conclusion of the experiment the survival per pot was recorded, as well as the height of live seedlings to the nearest millimeter.

Effect of Sodium Tetrphosphate on Ponderosa Pine Germination and Growth (Experiment C)

A separate experiment testing the effect of sodium tetrphosphate (Sod. Tet.) on germination of seeds and on 1-mo-old seedlings was conducted because the chemical was not available at the time the other two experiments were run. The experiment was conducted in the same manner as the other two experiments, except that the seeds used were collected on the Sitgreaves National Forest. These seeds had a higher germination

percentage (98 vs 70%) than those in the preceding experiment, which were collected on the Cocomino National Forest.

Results of "Effects of Chemicals on Seedlings" Experiments

The results from the three experiments were similar. The heights and survival of seedlings for all chemicals at the 0.1% concentration were the same as the control (figs. 1 and 2). The FeCl_3 treatments at 0.5 and 1.0%, and CaCl_2 and tripoly at 1.0%, had no surviving seedlings after 1 mo in Experiment A. In Experiment B, FeCl_3 at 0.5 and 1.0% and tripoly at 0.5% reduced height growth ($P = .01$). Calcium sulfate at all rates had no detrimental effect on survival and subsequent growth in either experiment. Sodium tetrphosphate did not adversely affect germination or subsequent survival in Experiment A (fig. 1), but the 1.0% rate reduced survival and height growth of 1-mo-old seedlings in Experiment B:

Chemical concentrate (%)	Survival (%)	Mean height (mm)
Control	100	57
0.1	100	54
0.5	96	52
1.0	52	44

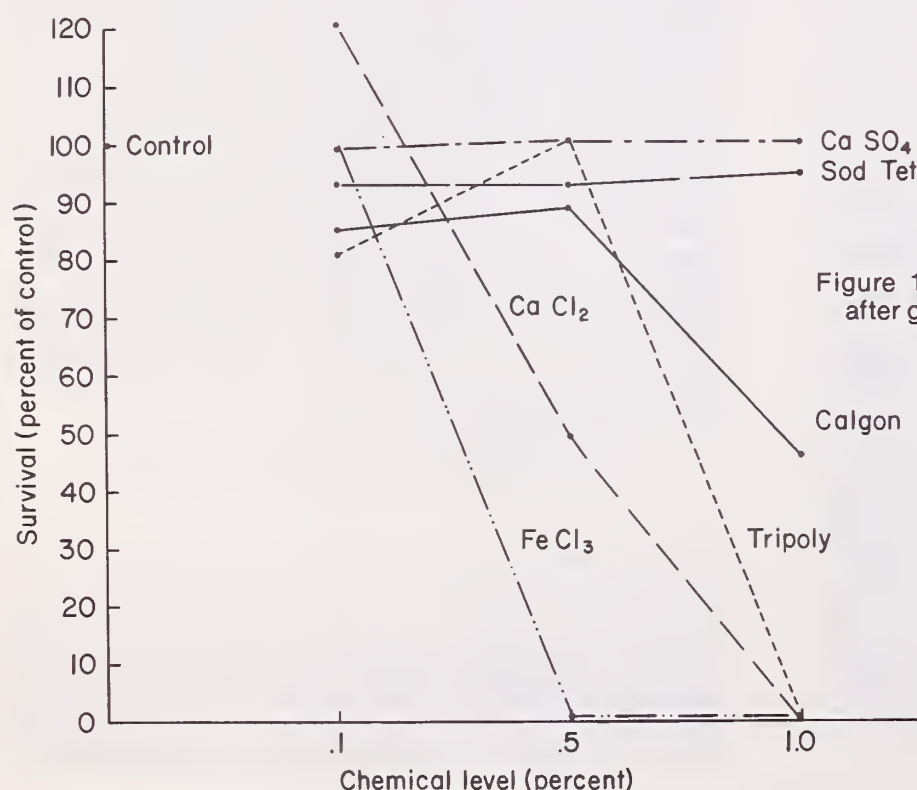


Figure 1.—Survival of ponderosa pine seedlings 1 mo after germination in sand treated with various chemicals.

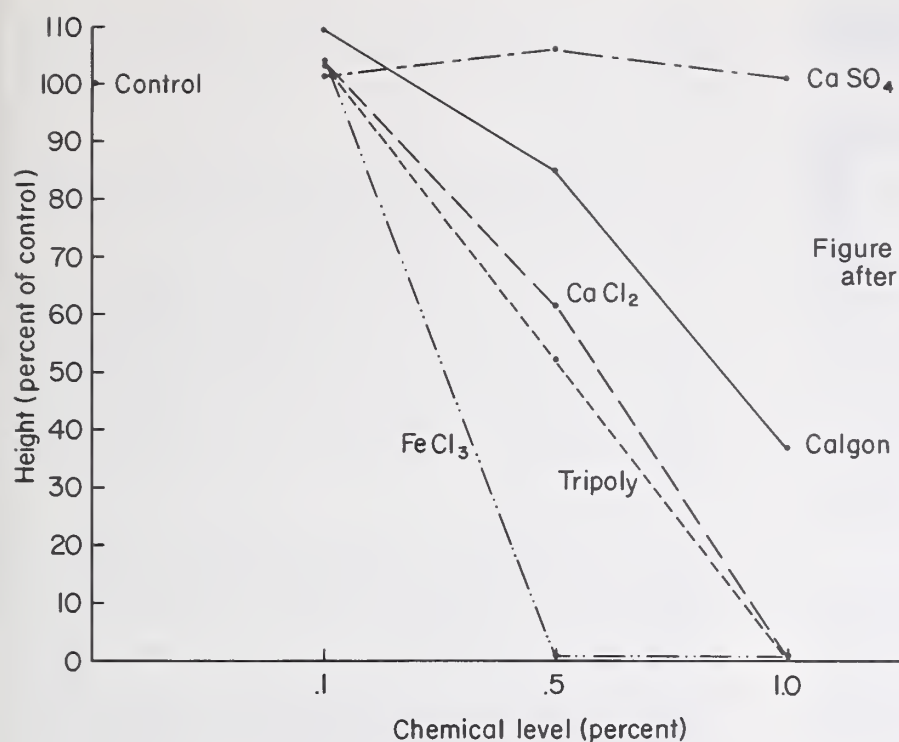


Figure 2.—Heights of ponderosa pine seedlings 1 mo after germination in sand treated with various chemicals.

Effects of Chemicals on Soil Heaving

Most of the chemicals that did not significantly reduce germination and growth of ponderosa pine in the pot experiments were tested for their effectiveness in reducing the heaving of two soils in laboratory experiments. The soils used were the 2.5- to 7.6-cm depths from Tie Park and Beaverhead Flat:

	Tie Park	Beaverhead Flat
Bulk density	1.08	1.79
Sand, %	1	52
Silt, %	66	34
Clay, %	33	14
Organic matter, %	1.93	0.20
Texture	Silty clay loam	Sandy loam

Previous experiments indicated that these two soils were highly susceptible to frost heaving (Heidmann 1975). Each soil was tested in separate experiments in the freezing chest. In each experiment the following treatments were used: Sod. Tet., 0.1%, 0.5%; CaCl₂, 0.1%; tripoly, 0.1%, 0.5%; FeCl₃, 0.1%; CaSO₄, 0.1%, 0.5%, 1.0%; X-77 (a wetting agent), 0.1%, 0.5%; and control.

The amount of each oven-dried soil used was that necessary to duplicate the field bulk density when packed in the PVC cylinders. The soil samples were first placed in individual glass beakers. The amount of chemical needed per cylinder was calculated as 0.1%, 0.5%, and 1.0% of the mass of

each individual soil. This amount of chemical was added to the soil in the beakers and mixed dry. The soil-chemical mixtures were packed in the PVC cylinders, which were then placed in pans of water to soak until a constant weight was reached. Wet weights of the cylinders were determined to the nearest 0.1 g. Next, the cylinders were placed on paper towels and allowed to drain overnight, after which they were placed in an oven and dried at approximately 40°C for 24 h. The cylinders were removed from the oven and again weighed to the nearest 0.1 g. The cylinders were then placed back into their original beakers and allowed to reach a constant weight once more. The cylinders were dried and rewetted in an attempt to simulate field conditions, and also to enhance the effect of FeCl₃. As the soil dries, FeCl₃ cements the soil particles together, thus restricting water movement in the soil. The cylinders were randomly assigned locations in the freezing chest, which was then placed into the freezer, and freezing trials were conducted in the manner described previously (Heidmann 1974).

During the experiment the cylinders were checked every 8 h to determine the onset of freezing. At the conclusion of the experiment, the cylinders were removed from the chest, and heaving was measured to the nearest millimeter. The depth of frozen soil was also measured to the nearest millimeter.

Several chemicals reduced heaving for both soils (fig. 3, table 2). Most of the chemicals reduced heaving of the Beaverhead Flat soil. Calcium chloride and FeCl₃ reduced heaving 84% and 81%,



Figure 3.—Soil from the 2.5- to 7.6-cm depth at Beaverhead Flat, treated with chemical additives to reduce frost heaving. From the left, the treatments are control; X-77, 0.5%; ferric chloride, 0.1%.

respectively. In addition, Sod. Tet., calgon, and tripoly—all at the 0.5% rate—reduced heaving over 50%. Heaving was increased by X-77, probably because X-77 reduces the surface tension of the water, which results in better capillary flow of soil water to the freezing front.

The time required for onset of freezing was also recorded for each sample (table 2). Over 180 h elapsed before samples treated with CaCl_2 and FeCl_3 began to freeze, which far exceeded the initiation of freezing in other samples and was

approximately four times the control. Several samples, mainly CaSO_4 and X-77, began freezing before the control. The time to initiate freezing was negatively correlated with total heaving ($r = -0.72$).

The results with the Tie Park soil are similar to those with Beaverhead Flat. Most of the chemicals reduced heaving, but only CaCl_2 resulted in a reduction of over 50% (table 2).

Differences in time to initiate freezing were not as great as those for Beaverhead Flat (table 3). Samples treated with CaCl_2 and FeCl_3 took 82 h to begin freezing, about twice as long as the control. Time to initiate freezing and total heaving were again negatively correlated, but this time the r value was -0.62 .

Heaving characteristics of the two soils appear to be different. The control from Tie Park heaved 12.8 mm compared to 21.5 mm for Beaverhead Flat. In another heaving experiment, using soil at field bulk densities, the results were similar. In still another experiment, however, in which frost heaving of soils was studied at different bulk densities, heaving of Tie Park soil was greater than from Beaverhead Flat (Heidmann and Thorud 1975). In all soil freezing experiments conducted, heaving increased directly with bulk density.

The results from these experiments indicated that FeCl_3 , CaCl_2 , and several other chemicals at

Table 2.—Effects of chemicals on amount of heaving and time required for onset of freezing

Treatment	Rate of application	Beaverhead Flat				Tie Park			
		Total heave	Time to freeze		Total heave	Time to freeze		Total heave	Time to freeze
	Percent	mm	Percent of control	Hours	Percent of control	mm	Percent of control	Hours	Percent of control
CaCl_2	0.1	3.5	-84	186	+288	5.5	-57	82	+71
FeCl_3	.1	4.0	-81	182	+279	6.5	-49	82	+71
Sod. Tet.	.5	7.5	-65	59	+23	6.5	-49	64	+33
	.1	13.5	-37	46	-4	10.5	-18	52	+8
Calgon	.5	7.8	-64	88	+83	7.2	-44	54	+12
	.1	12.0	-44	50	+4	10.1	-22	58	+21
Tripoly	.5	10.2	-53	88	+83	7.8	-39	62	+29
	.1	11.5	-47	48	0	12.5	-2	56	+17
CaSO_4	1.0	14.2	-34	44	-8	7.0	-45	62	+29
	.5	11.5	-47	42	-12	8.2	-36	60	+25
	.1	21.5	0	40	-17	11.0	-14	46	-4
Control		21.5	0	48	0	12.8	0	48	0
X-77	.5	23.8	+11	42	-12	16.2	+27	60	+25
	.1	21.0	-2	42	-12	13.0	+2	48	0

Table 3.--Effect of chemicals on heaving of dowels, plug seedlings, and tubelings at S-3, April 1974

Treatment ¹	Rate of appli- cation	Plug seedlings			Tubelings			Dowels	Average
		Live	Dead	All	Live	Dead	All		
	<i>Percent</i>	<i>Mean heaving per row (mm)</i>							
Sod. Tet.	0.5	6.0	5.7	5.2	19.0	22.7	21.0	10.9	12.9
CaSO ₄	1.0	5.4	5.6	5.9	17.9	18.9	18.4	7.4	11.4
Cultivation		10.1	11.2	11.2	32.7	33.7	33.0	19.9	21.7
CaCl ₂	0.1	11.4	16.3	11.5	26.1	47.4	37.9	17.5	24.0
FeCl ₃	0.1	6.8	9.2	8.2	27.4	39.2	30.4	8.6	18.5
Control		12.2	19.7	13.7	30.1	57.6	44.5	21.0	28.4
Average		8.6	11.3	9.3	25.5	36.6	30.9	14.2	19.5

¹All chemical control treatments include cultivation.

rates not toxic to ponderosa pine seedlings might control heaving of susceptible soils. These results were the basis for the field trials to be discussed next.

Field Experiments

All of the field experiments were conducted within a rodentproof enclosure at Unit S-3 of the Fort Valley Experimental Forest. Unit S-3 is approximately 6 mi west of the Experimental Forest headquarters.

Chemical Control Methods, 1972

During the summer of 1972 an experiment was installed to field-test chemicals for their effectiveness in controlling frost heaving. Chemicals used were those that did not inhibit germination of ponderosa pine seed or substantially reduce survival of seedlings in the laboratory experiments. The experiment was a failure. One of the main causes of failure may have been the unusually heavy precipitation, over 10 inches, which fell on the study area during October. The normal October precipitation at Fort Valley is less than 2 in (fig. 4).

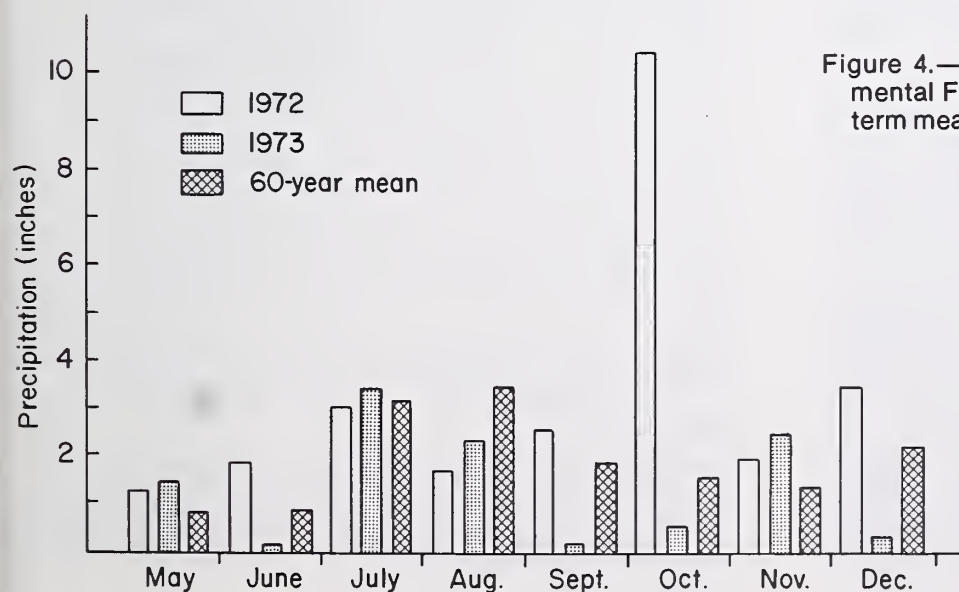


Figure 4.—Precipitation at Unit S-3, Fort Valley Experimental Forest, during 1972 and 1973 compared to long-term means.

The precipitation, mainly in the form of rain, may have washed a good portion of the chemicals from the plots, since they were only mixed into the top 2.5 cm of soil.

Chemical Control Methods, 1973

In 1973 an experiment was installed with the following treatments:

1. Control.
2. Cultivation.
3. 0.1% FeCl_3 and cultivation.
4. 0.1% CaCl_2 and cultivation.
5. 0.5% Sod. Tet. and cultivation.
6. 1.0% CaSO_4 and cultivation.

A piece of sheet metal 10 cm high was pounded into the soil to a depth of approximately 5 cm along each plot border, to prevent washing of chemicals from the plots. The chemical rates were again based on the mass of the soil. This time, however, the chemicals were applied to the top 7.6 cm of soil instead of the surface 2.5 cm. The cultivation treatment was based on earlier results that indicated frost heaving was directly related to the bulk density of the soil (Heidmann and Thorud 1975). Loosening the soil lowers its bulk density.

All chemicals except FeCl_3 were applied to the plots dry and mixed into the top 7.6 cm by cultivating the soil with small hand rakes. Ferric chloride was first dissolved in water and then sprinkled on the plot surface. After allowing the surface of the plot to dry, the soil was cultivated in the same manner as in the other plots. Treatments were applied on July 24, 1973.

Each plot contained three rows, which were planted with five tubelings, dowels, or plug seedlings.

Plug seedlings were raised in styrofoam blocks. Plugs were 1 cm in diameter and 11 cm deep. The plug seedling was pulled from the block and planted with the accompanying soil medium. Tubelings were raised in plastic "Ontario" tubes approximately 1.2 cm by 7.6 cm. The seedling and tube were planted together. The plug seedlings were about 6 mo old while the tubelings were approximately 2 mo old. Dowels were simply wood cylinders 3.2 mm in diameter and 20.3 mm long.

On September 19, before heaving conditions developed, all of the tubelings, dowels, and plugs were measured to determine a reference point for later heaving measurements. The heights of seedlings were measured to the terminal buds. The dowels were measured by determining the amount that each dowel projected above the soil surface. These measurements were subtracted from later measurements to determine amount of heaving.

After the initial measurements, the plots were checked frequently to determine the onset of heaving.

The late summer and fall of 1973 were dry. It was necessary to water the plots not only to insure there would be seedlings alive for observation, but to provide moisture for frost heaving. For frost heaving to occur, the soil must be close to pore saturation (Heidmann and Thorud 1975). Soil moisture samples collected from the study area after repeated watering indicated that soil moisture content ranged from 30 to 50 percent on an oven-dry weight basis. These moisture contents led to heaving, but not at rates that have been observed at S-3 in the past. Heaving was observed on all plots on November 7, 1973. The following few days little heaving was noted. On November 18, over 30 cm of snow fell on the study area and it was not possible to measure heaving again until spring 1974. The data analyzed are from the final measurements taken in April 1974.

Heaving on chemically treated plots was 41% less than on the control, and 23% less than for cultivation alone (table 3). On CaSO_4 and Sod. Tet. plots, heaving was reduced 60% and 55%. Overall, heaving of tubelings was three times as great as for plug seedlings. Tubelings heaved the least on CaSO_4 plots.

Survival on control plots was not different from the mean of the other treatments (table 4). Survival on chemically treated and cultivated plots was 55% greater than for cultivation alone ($P = 0.055$). The best survival—73% on plots treated with CaSO_4 —was 54% better than the control. Tubelings on these plots had the highest survival in the experiment (78%).

Table 4.--Survival of plug seedlings and tubelings planted on plots treated with various chemicals in 1973

Treatment ¹	Rate of appli- tion	Plug seed- lings	Tube- lings	Average
- - - - - Percent - - - - -				
CaSO_4	1.0	68	78	73.0
Cultivation		35	38	36.5
Sod. Tet.	0.5	58	38	48.0
FeCl_3	0.1	50	42	46.0
CaCl_2	0.1	75	45	60.0
Control		45	50	47.5
Average		55.2	48.5	51.8

¹All chemical control treatments include cultivation.

Overall, the survival of plug seedlings and tubelings was not impressive, although both tubelings and plug seedlings did well on CaSO_4 plots. The poor survival of plug seedlings may be because the seedlings were not vigorous enough. Subsequent plantings of plugs containing older seedlings have given survivals as high as 95%.

Coarse Sand, 1972

A preliminary field experiment in 1971 indicated that planting "Ontario" tubes in coarse sand reduced frost heaving. Reduced heaving was believed due to the fact that water in sand does not segregate (Taber 1929). Another experiment testing coarse sand as a method of controlling heaving of tubelings was installed in 1972. The results from this experiment indicated no differences in heaving between control, tubelings planted in holes filled with sand, or tubelings planted with a 1.2 cm mulch of sand.

Coarse Sand and Other Control Methods, 1973

In 1973, another experiment testing coarse sand as a method of reducing heaving of tubelings was tried because of the contradictory results from the 1971 and 1972 experiments. In addition, tubelings and plug seedlings were planted below the soil surface in an attempt to simulate silting. The heavy rains in October of 1972 resulted in many tubes being silted over. These tubes did not appear to heave.

The experiment consisted of eight plots approximately 1.0 m by 0.9 m. Within each replication, the following six treatments were tested:

1. Plug seedlings planted level with the soil surface (control for plug seedlings).
2. Plug seedlings planted 1.5 cm below the soil surface, with the resultant hole being filled with soil as in Treatment 5.
3. Tubelings planted without sand (control for tubelings).
4. Tubeling planted level with the soil surface, with coarse sand placed into the planting hole as in preceding studies.
5. Tubelings planted 1.5 cm below the soil surface with the resultant hole filled with soil (buried).
6. Tubelings planted as in Treatment 3, but without filling the hole with soil (countersunk).

Planting was done using hardwood dowels to make the planting holes. Within the plots the tubelings and plug seedlings were planted at a spacing of 15 cm. The plots were hand watered

periodically after planting because of drought conditions. On September 19, the heights of the seedlings were measured to the nearest millimeter to get a reference point for later heaving measurements.

Treatments reduced heaving and improved survival:

Planting treatment	Mean heaving per row (mm)	Survival (%)
Plugs:		
1. Regular depth (control)	17.2	7.5
2. Buried	14.9	27.5
Tubelings:		
3. Regular depth (control)	53.9	12.5
4. Sand, regular depth	28.3	77.5
5. Buried	37.4	37.5
6. Countersunk	24.0	62.5

Highest survival was 77.5% for tubelings planted in coarse sand (4) compared to 12.5% for the control (3). The average survival for plug seedlings (1,2) was 18%, compared to 25% for comparable tube treatments 3 and 5. The overall survival of tubelings was considerably better (47.5%) than for plug seedlings (17.5%) ($P = .01$).

Plug seedlings (1,2) heaved about 55% less than tubelings (3,4,5,6). Treatments 4 and 6 heaved about 50% less than the control (3). Subsequent experiments confirmed that plug seedlings heave far less than tubelings. Plug seedlings rarely heave completely out of the ground, while tubelings commonly do.

Supplemental Instrumentation

A number of instruments were maintained on the study area at S-3 to record climatological data.

A continuous record of air temperature and humidity 10 cm above the soil surface was obtained with a Lambrecht hygrothermograph located within a standard U.S. Weather Bureau instrument shelter from which the legs had been removed. A maximum-minimum thermometer was also located within the shelter. Temperatures 15 and 2.5 cm above the soil surface as well as at and 2.5 cm below the surface were measured periodically with copper-constantan thermocouples.

Net radiation 30 cm above the ground was monitored continuously during the frost heaving period of 1973 with a Kahlsico radiation probe connected to an Esterline Angus spring-wound strip-chart recorder.

Precipitation was measured over a 2-yr period beginning in the fall of 1971 with a standard U.S. Weather Bureau rain can.

To more closely observe and record the heaving phenomenon, time-lapse motion pictures were taken during the frost heaving season in 1973. The camera used was a Minolta D-4 Autopak super 8 mm with flash synchronization and an electronic timer to regulate the time interval. The pictures were taken at an interval of approximately 3 min on high-speed Ektachrome film (ASA 160).

Supplemental Field Observations

A mild period in early December 1973 resulted in melting of the snow on several plots in the 1972 study area, which was located adjacent to the 1973 study. Because of their location, the plots in the 1972 study area received more sunshine than the 1973 plots. As a result, the heaving of tubes was observed from December 12 to 19. The time-lapse camera was set up to take pictures of one row of eight tubes, which had already partially heaved out of the ground. The radiometer was set up near the plot, and maximum and minimum temperatures were recorded every day. The moisture content of the top 2.5 and 15 cm of soil was determined twice during the period.

One of the important findings (table 5) was that the moisture content of the top 2.5 cm of soil was over 50% at the beginning of the period. The

Table 5.--Summary of supplemental field observations made December 12 to December 19, 1973 at S-3

Dec. 1973	Net radia- tion	Temperature		Number of tubes	Mean heave	Soil moisture at depth (cm) of--	
		Maxi- mum	Mini- mum			0-2.5	0-15.2
	<i>Langley's per day</i>	<i>°C</i>	<i>°C</i>		<i>mm</i>	<i>Percent</i>	
12	-195.09						
13	-59.10	+8.3	-5.6		3.5	50.7	40.7
14	-72.98	+8.9	-8.9	8			
15	-86.55	+10.0	-5.6	8	6.1		
16	-31.19	+12.8	-3.3	8	6.1	48.1	39.0
17	-64.87	+12.8	-4.4	8	3.6		
18	-245.77	+5.0	-5.0	7	5.7		
19		+10.0	-12.2	4	4.8		
Total	-755.55	+67.8	-45.0				
Mean	-107.94	+9.7	-6.4		5.0		

moisture content of the top 15 cm was 40%. Three days later the moisture content had dropped approximately 2% at each depth. The minimum temperature averaged 6.7°C (20°F). Net radiation was negative throughout the period, ranging from -31 to -246 ly per day. The eight tubes heaved an average of 27 mm during the period, with a mean heave of 4.8 mm per night. The soil was checked every afternoon to determine if permanent frost

was present. There was none until December 20. On some mornings the needle ice layer was 2.5 cm thick. In several areas, needle ice formed at the surface without a cap of soil, which indicates exceptionally wet conditions (fig. 5) (Outcalt 1969).



Figure 5.—Ice layer approximately 2.5 cm thick composed of needle ice. Note that needle ice has formed at the surface in the foreground, indicating that the soil is very wet.

During the observation period, four of the eight tubes heaved completely out of the ground.

The time-lapse pictures confirmed that heaving was the result of a number of freeze-thaw cycles.

DISCUSSION AND SUMMARY

Frost heaving is caused by segregation of soil water, which freezes into layers of ice. The lenses lift the solidly frozen soil surface, which grips the seedling stem. When the lenses melt the soil recedes, but the seedling remains extruded on the surface.

Chemicals that did not damage young ponderosa pine seedlings or hinder germination reduced heaving significantly in the laboratory and the field. Calcium sulfate was the only chemical tested that did not reduce growth or germination at all rates.

Results from another study indicated that CaSO_4 depressed germination on a freshly burned area (Rietveld and Heidmann 1976). This may have been the result of fire-induced water repellency and its effect on soil cation exchange capacity. Since water repellency results from coating of soil particles with a hydrocarbon film (Savage 1974), soil cation exchange capacity would be substantially reduced or eliminated. The effect

would be to increase the concentration of the chemical in the soil solution to a level that may have been high enough to be toxic to germinating seeds.

Of three experiments conducted with "Ontario" tubes planted in coarse sand, heaving was significantly reduced in the first, while results were mixed in the other two. The first experiment was not installed until late in the fall. The second and third were both begun in the summer, allowing a period of 8 to 10 weeks during which fine soil material could be washed into the sand by precipitation. Casagrande (1931) stated that a small amount of fine material, as little as 1% to 3%, mixed in coarse soil such as a gravel, will result in segregation of water. Enough fine particles may have become mixed with the sand in the summer plantings, because of precipitation and watering, for segregation of water to occur when conditions become suitable for heaving.

Tubelings planted in coarse sand had a higher survival percentage than seedlings in the other treatments. Survival may have been higher because moisture penetrates the coarse sand easily and reaches the base of the tube where the seedling roots are. Even small amounts of precipitation may penetrate to this zone. With the other planting treatments, moisture must penetrate 7.6 cm of fine soil before reaching the root zone. In drought periods, such as occurred in 1973, this difference can be an important factor.

A significant finding of the study was that tubes covered by a layer of soil did not heave readily. This information, along with observations of dowels in previous years, indicates that heaving is a surface phenomenon. The same conclusion was reached by Fahey (1973) after studying frost heave cycles at different soil depths.

The results from the tubeling experiments indicate that planting tubes below the soil surface in coarse sand would tend to increase survival and reduce heaving. The plug seedlings do not appear to heave regardless of planting method, possibly because they are older (6 mo) and have a more rigid stem. The plug seedlings are thus capable of producing a gap around the stem at the ground-line (Schramm 1958). In addition, plug seedlings are raised in a coarser medium in which segregation of water may be limited. A complete description of the heaving mechanism is given by Heidmann (1976).

Chemical treatments appeared to reduce heaving in the field studies, although observations were limited in 1973 by climatic factors. Survival of seedlings in the field was lowered somewhat by chemicals, but the rates used were three times as high as those used in the laboratory. Survival of seedlings on cultivated plots was low, but heaving was substantially reduced. Why cultivation should result in lower survival is not clear.

Field observations substantiated that frost heaving is a phenomenon that requires wet soils. It was not possible by hand watering to initiate significant heaving in 1973. When sufficient precipitation fell to raise the moisture content of the surface 2.5 cm of soil to 50% and higher, heaving was rapid.

Observations in the field indicate that differences in frost heaving on plots are related to soil moisture content. Soil moisture in the top 2.5 cm of soil varied by as much as 13% in samples collected within 16 cm of each other. Tubes or dowels this distance apart often heaved at greatly different rates. It was common to observe two tubes heaved completely out of the ground, while a tube between them had heaved only a few millimeters. The differences in heaving are believed to be due entirely to soil moisture content.

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Frost heaving is a three-step process: (1) The surface layer of soil freezes and grips the seedling stem tightly. (2) Ice lenses form below the surface, lifting the seedling and frozen soil. (3) When the soil thaws, it settles back loosely to its original position, leaving the seedling on the surface. Plowing to reduce soil bulk density and adding gypsum to lower the freezing point of soil water will reduce frost heaving.

Keywords: Frost heaving, regeneration methods, *Pinus ponderosa*.

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